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SOME PERSPECTIVES AND RECENT FINDINGS IN SHALLOW WATER ACOUSTICS

By
R. J. Urick

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NAVAL ORDNANCE LABORATORY, WHITE OAK, SILVER SPRING, MARYLAND

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Shallow water acoustics has had in this country a long, though sporadic, history dating back to World War II, when the acoustic mine stimulated feverish activity in the subject. Yet, in spite of the impressive body of theory, model studies, and field data that has accumulated in subsequent years, many aspects of this most difficult branch of underwater acoustics are not understood. Many of its complications are due to the temporal and spatial variability of the shallow water medium and its boundaries. For example, we have found the transmission of shallow water sound to vary with direction and time at one location and to be different at apparently similar locations. Such variations make acoustic prediction difficult, and necessitate on-the-spot measurements at the place and time that data is required. To this end, we have developed and tried out at a number of coastal locations an airborne method of data collection using sonobuoys, explosive sound signals, and simple, portable recording equipment. The transmission results have been summarized by loss contour charts showing the transmission environment around a receiving point in shallow water.

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NAVAL ORDNANCE LABORATORY
Silver Spring, Maryland

8 November 1971

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This report summarizes some of the problems, and presents some recent research results, on the difficult subject of underwater sound in shallow water. It was presented as an invited paper on shallow water acoustics at the 82nd meeting of the Acoustical Society of America.

The report is based on work done under an NOL Shallow-Water research program funded by task number A370-370A/WF121-702, Problem 203.

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Captain, USN
Commander

Z.I. Slawsky

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By direction

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SOME PERSPECTIVES AND RECENT FINDINGS IN SHALLOW WATER ACOUSTICS*

HISTORICAL REVIEW

At the Houston meeting of the Society a year ago, a series of invited papers were presented under the title, "The Past Twenty Years in Underwater Acoustics". One of the subjects not covered specifically in these survey papers was shallow water acoustics. This morning, I would like very briefly to rectify this deficiency - without admitting a senility of both subject and speaker that a historical approach implies - but rather as a way of setting the stage, so to speak, for an understanding of what is now going on in the subject, and why.

It all began, like most phases of underwater acoustics, in the dark days of World War II, when there emerged two crushing, pressing problems. One was dictated by the needs of the then newly-developed acoustic mine. Here it was necessary to know something about the radiated noise of ships, and how this noise propagated to a distance, in order to be able to set the sensitivity of mine mechanisms and to know the distance from acoustic sweep gear at which they were likely to be swept. This need for knowledge in acoustic mining prompted the establishment of a number of sound ranges on our East and West coasts and motivated the first theoretical studies of sound transmission in shallow water. The frequencies of interest were low, and the properties of the bottom were even then recognized to be important.

At a much higher frequency occurred the other major World War II problem in shallow water. This was the protection of harbor entrances and approaches against submarine sneak craft. Here remote hydrophones cable-connected to shore and an echo-ranging set called HERALD, were developed and used. Because the frequencies - near 24 kHz - were high and ranges were short, the peculiarities of the environment were restricted to those of the volume of fluid - such as biological organisms and turbulence phenomena - rather than to the surface and bottom that are so important for long distance propagation.

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*Invited paper presented at the 82nd meeting of the Acoustical Society of America, Denver, Colorado, October 1971.

In the post-war years, a major event for shallow water acoustics in this country was the Korean conflict, which stimulated much activity in mine countermeasures for a few years. Project BEAVERTAIL was a major undertaking in the years '53 to '56. Indeed, a count of papers published in shallow water acoustics shows, not surprisingly, a peak of publishing activity during this period.

But, while all of these applications of shallow water acoustics are interesting and fascinating, there remains the problem of long-range submarine detection in shallow water. Here the waters of interest are those of the continental shelves between depths of, say, 100 and 600 feet; the ranges of interest extend out to many miles in keeping with the capabilities of modern active and passive sonars. From the research point of view, field measurements began in World War II with the work of Worzel and Ewing and, on the theoretical side, the work of Pekeris; these findings were published in - of all places - Geological Society of America Memoir 27, dated 1948. Subsequently, the problems of long-range shallow water acoustics have occupied numerous theoreticians, and a large number of cases have been treated theoretically - all of them more or less idealistic models of the real world. Field measurements exist in abundance and numerous transmission runs can be compiled for shallow water locations in many areas of the world. A bibliography of shallow water acoustics in all its aspects would comprise several hundred entires.

This subject - long range shallow water transmission - has received world wide attention, particularly in those countries that are surrounded by broad stretches of shallow water. Figure 1 is a Mercator chart of the world, where waters less than 100 fathoms deep have been shaded in. Here we note the extensive areas in the Baltic countries, the United Kingdom, the north coast of Australia and the east coast of Argentina, all of which to some extent have contributed to its literature. The vast extent of shallow water north of Soviet Russia is particularly impressive, in spite of the distortion of the Mercator projection.

Yet in spite of this activity by many theoreticians and experimentalists - notably in those countries having a more vital interest in shallow water ASW than we have - our ability to make predictions for shallow water is far poorer than it is in deep water. We do not have the quantitative understanding of various phenomena we need for making accurate predictions - which, after all, is the final result of research on an environment that cannot be altered or controlled.

VARIABILITY IN SHALLOW WATER ACOUSTICS

Most of our troubles with the subject appear to stem from the variability of shallow water acoustics - both temporally and spatially. This variability we do not always understand and cannot always explain. Variability seems to be inherent in the shallow water environment itself, subject as it is to temporal changes in such things as the weather and near-shore currents and the spatial changes in such properties as salinity and bottom composition.

We have encountered some forms of variability in our own shallow-water research program. To give you an idea of what I mean, I would like to present some examples of variability as they have appeared in our own findings.

1. CW Transmission

Figure 2 is a chart of a location off Ft. Lauderdale, Florida where a sound source was placed on the bottom in 60 feet of water along with several hydrophones in a cluster some 5000 feet to the south. We transmitted continuously from source to hydrophones. Figure 3 shows the level of a cw 1120 Hz tone as received over a period of a couple of days. Each plotted point is an average over a 15 minute period. Down below is the height of the tide. Apparently the 2 to 3 foot tidal change is accompanied by a 10-15 db change in the transmitted sound. The explanation of this variability was not hard to find. When we made a reasonable assumption about the magnitude of the bottom loss, we found that two effective transmitted modes occurred. These two modes interfered with one another every 6 hours as the water depth changes and caused the deep fades that were observed. At shorter ranges, where many modes exist, and at longer ranges where only the first mode remains, such deep fades would not be expected to occur.

2. Directional Effects

Not so readily explained are some differences observed in another experiment. Figure 4 shows an area off the west coast of Florida in the Gulf of Mexico, where the bottom was very gently sloping. A research vessel was anchored at the center of the cross in 200 feet of water and 60 foot explosive sound signals were dropped by an aircraft along the arms of the cross oriented so as to be parallel and perpendicular to the bottom slope. The length of the arms was 50 miles.

The results were worked up in the manner shown in Figure 5, where we have plotted transmission loss in octave bands from 25-50 Hz to 3200-6400 Hz along one of the arms (Run B of Figure 4 extending to the South) for a hydrophone at a depth of 80 feet. Here the straight lines denote spherical or free field spreading.

We note, relative to these lines, that the transmission tends to be better than in the free field at short ranges and poorer at long. At long ranges the data drop rapidly below the line when plotted on a logarithmic range scale. This is typical of shallow water: better transmission than in the free field at short ranges due to trapping in the shallow duct, and poorer at long ranges due to boundary and volume attenuation.

But plots such as these were found to have some mysterious features. For example, the next figure (Fig. 6) compares the run to the north (Run A) with the run to the south (Run B) in water of constant depth of 200 feet, plus or minus a few feet. Notice that at low frequencies (50-100 Hz) the transmission to the North (shown by the crosses) is much poorer than that to the South (shown by the circles) by some 30 db at 40 miles. Yet at a high frequency, the reverse is the case, the North run being better in transmission than the South run. Strange to say, the water depth, the thermal structure and the bottom type are all apparently the same in these two directions. We must blame some difference in the deep bottom structure or composition - about which nothing is known at this location - for this sort of difference.

In the other two directions of the cross - up and down slope - a peculiarity was found as well. In Figure 7, the transmission runs in the two directions are compared. Upslope (Run D) is better than downslope (Run C) at a high frequency and about the same at a low frequency. Here the source and receiver depths were shallow and the high frequency transmission was therefore dominated by propagation in the mixed layer. An explanation for the better transmission toward shallower water may be a lower leakage out of the layer due to the increasing proximity of the bottom in this direction.

3. Seasonal Effects

Seasonal changes have been noted by every investigator having an opportunity to make observations in the same area over a period of time. Such changes may result simply from seasonal changes in the temperature gradient in the water column. We had an opportunity to return to the site of the cross at another season of the year and to make some repeat measurements. The first time, in October, when we got the results just shown, the mixed layer was 120 feet thick and occurred on top of a negative gradient; in March, the mixed layer was absent, and a gentle negative gradient extended all the way down to the bottom. Figure 8 compares the transmission on the two occasions. Here the light crosses and circles, connected by lines, show the same data as before, for Run B to the South for an 80 ft hydrophone depth and a 60 ft source depth, when a well developed mixed layer 120 feet thick existed. The newer data - in the absence of a mixed layer - is shown by the large solid dots. Notice, first, the similarity in transmission at frequencies too low to be trapped in the 120 ft duct and therefore too low to be affected by its absence. But the higher frequencies, in the 400-800 Hz band and above, show much poorer transmission when the duct was absent - in March - than when it was present - in October, as one would expect.

4. Ambient Background

At this point, I would like to leave transmission and turn briefly to the ambient noise background. In shallow water as well as in deep, we know that there are three principal sources of the noise background: one, ship traffic, two, wind action on the surface and three, biological sources. These three sources produce noise having different spectral characteristics; they are readily distinguishable by listening. Since these noise sources are variable in magnitude from time to time and place to place, one might expect the shallow water background to reflect this variability. We had the opportunity to record and analyze the noise background over a period of several weeks at two different shallow water sites off our East Coast. These locations are shown on Figure 9. One was in the Gulf of Maine, the other was off Ft. Lauderdale. Both were in about 300 feet of water a few miles from shore. At each site, a hydrophone, laid on the bottom and cable connected to shore, was used. Noise samples one minute long taken every hour. Some samples are shown in Figure 10. Here are shown some typical hourly samples each one minute long over a 24 hour period. They are labeled according to the major source of noise, as identified by listening to the samples. We observe that the Florida Coast site is, in the frequency band 100-200 Hz shown here, more noisy and more variable from sample to sample. Consecutive hourly samples differ sometimes by 20 or 30 db. These differences are caused by the larger amount of miscellaneous ship traffic at the Florida coast location. Figure 11 shows the spectral statistics at the two locations. In spite of the fact that sound propagation is much better in the Gulf of Maine than off the Florida Coast, the Florida Coast site is some 5-10 db more noisy at low frequencies - because of the greater noise contamination by ships. By contrast, the two sites are quite similar at 1 kHz and above, where the spectrum was dominated by wind noise. Indeed, as it happens, when high frequency noise measurements made at many shallow water sites are plotted together, they are remarkably concordant, provided they are free of ship noise and noise from biological sources. We may see this on Figure 12 where we have the level of 1 kHz noise observed at widely separated sites and reported in the literature, plotted against wind speed prevailing during the measurements. We find, somewhat surprisingly, that the widely scattered measurements, made by different individuals at different times over the past 25 years, using different hydrophone and measurement systems, in different water depths, are concordant - not only with themselves, but with the Knudsen values for deep water ambient noise as a function of wind speed. The solid curve shows the Knudsen ambient noise levels at 1 kHz, plotted against wind speed. The reason for the agreement is that wind noise originates at the sea surface over the measurement hydrophone within an area of surface about equal in radius to the hydrophone depth. The level of this noise is independent of hydrophone depth and propagation conditions, and depends, as shown here, only on wind speed in the absence of noise pollution by ships and biological noise makers. This means that for prediction purposes, the level of the ambient background at a new, unmeasured shallow water site could be estimated from a knowledge of wind speed at that site, modified by an estimate of the density of shipping and biological sources. Such a prediction would become increasingly poorer at low frequencies where wind noise no longer dominates the spectrum.

PREDICTION FOR A NEW SITE

Turning back once more to propagation, it would seem apparent that complexities of the shallow water environment would make prediction of what to expect at a new location, using what is known about the environment at that location, an extremely difficult matter - especially when ranges measured in miles are concerned. We simply do not have the detailed knowledge needed for long range acoustic prediction at an arbitrary shallow water location. Even if we did, it is doubtful if we could handle that knowledge in an accurate prediction model.

AIRBORNE ACOUSTIC MEASUREMENT SYSTEM

We have experimented with the idea of rapid airborne data collection for shallow water use. The idea here is to be able to collect acoustic data rapidly wherever it might be needed at short notice. Four pieces of equipment are needed in this method: an airplane, some explosive charges as sound sources, a sonouboy, and some recording electronics. These four items are shown in the following photographs. Figure 13 is a picture of a P-3 Orion aircraft; this is the Navy's standard land-based ASW aircraft that exists in large quantities in the Fleet. Figure 14 shows an explosive sound signal Mk 61 that experience has shown to be a reliable source of wideband sound of known source level. Figure 15 shows a sonobuoy SSQ-48 consisting of, from top to bottom, a radio antenna, a float containing the electronics, connecting wire, cable reel, pre-amplifier, hydrophone, and a weight to keep the whole arrangement vertical in the water. In our work we have used calibrated SSQ-48 and SSQ-57 sonobuoys. Finally, Figure 16 shows the recording package, consisting of 4 sonobuoy receivers, a tape recorder, and a control and monitoring box. This equipment was purposely made portable in order that any aircraft having a sonobuoy antenna could be used.

A SHORT SHALLOW WATER SURVEY

With the system just shown, we made acoustic measurements at eight shallow water sites off our East and Gulf Coasts. These locations are shown in Figure 17. The eight sites were completed on four flight days during a single week. Figure 18 shows what was done at each location. A sonobuoy was dropped from the aircraft at the center of the pattern and explosive charges were dropped in various radial directions 45 degrees apart out to a distance of 30 miles. The sonobuoy hydrophone depth was 95 feet and shot depth was 60 feet. In addition, SSQ-36 bathythermograph buoys were dropped at the center of the pattern and at the ends of some of the radial arms. Aboard the aircraft, tape recordings were made of the received shot signals. Back in the laboratory, the recordings were filtered, squared and integrated, and then compared with the known energy spectrum of the source to give the transmission loss between shot and sonobuoy. Reverberation and noise measurements were also made. Figure 19 is a sample of the results at one of the stations. This busy figure shows both the acoustics and the environment. The traces at the corners of the slides are the BT traces at the ends of the radii; they show a mixed layer some 50 feet thick overlying a thermocline. The dotted lines are bottom contours taken from a chart; the bottom is gently sloping downward to the right between depths from 20 to 100 fathoms over the area. The numbers near each shot position give the measured transmission loss to the center, while the solid lines are transmission loss contours drawn from the measured loss values in the 100-200 Hz band.

Two aspects of the loss contours shown here, and as observed at the other stations, are noteworthy. The first is, that the values are contourable at all. For, it might be feared that because of multipath interference and the vagaries of shallow water transmission, the losses would be so random and so variable from shot to shot, that contours could be drawn only with difficulty, if at all. This would no doubt be the case with narrow analysis bandwidths; yet an octave band is apparently wide enough to smear out the spatial and temporal irregularities that are so evident in narrow frequency bands. The other feature I would like to mention is the elongation of the loss contours in the direction of the bottom contours. This elongation - a tendency for the contours to be elliptical rather than circular - means that the transmission is better in water of constant depth than toward deep or shallow water. We observed this effect at a number of the stations. The poor transmission upslope (toward more shallow water) may be the result of the larger number of bottom encounters in this direction, while the poor transmission downslope (toward deep water) may be the effect of downward refraction over a downward sloping bottom in carrying sound down below a shallow hydrophone.

INTER-LOCATION COMPARISON

When we try to compare the transmission at one location with that at another, we find some surprising differences from location to location. I would like to show an extreme example. Figure 20 shows transmission contours at two stations in an octave band centered at 63 Hz. At the left-hand location, the outermost contour is the 140 db contour and lies at a distance of about 20 miles. At the right-hand location, the outermost contour is 100 db at a distance of 30-40 miles. This amounts to a difference of some 60 db in transmission loss out to a distance of 30 miles. It indicates some profound difference in the shallow water environment. Yet it is hard to see what this difference might be. The octave bands at higher frequencies showed the same effect, though to a lesser extent. Figure 21 shows the depth contours and BT traces existing at the two places. At both places the bottom is gently sloping - downward to the southeast in one case and downward to the southwest in the other - with a depth of about 30 fathoms or 180 feet at the center of each of the two areas. The wavelength of sound at 63 Hz, by the way, is about 80 feet, so that the water is about two wavelengths deep at the center of the pattern. Not only is the water depth and bottom slope about the same in each case, but so is the BT - as shown by the traces obtained in various parts of the two areas. In both locations, a mixed layer 50 to 75 feet thick occurred over a steep thermocline followed by a more gentle thermocline down to the bottom. In short, as far as we have been able to tell from the water itself, the two areas are acoustically the same.

We turn then to the bottom itself. Here we find that, although the geology is the same - the structure consists of gently sloping sedimentary layers down to a depth of some 15,000 feet - there is an indication that the velocity profile in these sediments is different. Figure 22 shows the velocity profiles at the two stations - as kindly provided to me by the Shell Oil Company from seismic velocity measurements made a short distance from the two stations. Here we have velocity versus depth - with the location of poorer transmission at the left and the better transmission at the right, with one showing a uniform increase in velocity with depth down to about 11,000 feet and the other showing a more sudden discontinuity in velocity at 8000 feet - too shallow, I am told, to be the crystalline basement. What this difference might mean acoustically I do not know, but at least here is a possible tie-in to the profound difference in low frequency transmission that we found for the two areas.

SUMMARY

I would like to summarize matters - as they seem to me - in the following way: Shallow water acoustics over the years has received a great deal of attention, both on the measurement side and the theoretical side. Indeed, its problems still are fascinating. Propagation and noise measurements have been made in a variety of areas, and theoretical models have been worked out for a variety of circumstances ranging from the two fluid plane surface model to one involving a layered fluid over a solid layered bottom. Yet neither the theoretical models nor empirical models based on them do very well in predicting the transmission of sound in areas not yet measured. The difficulty lies in the variability of shallow water in space and time, and the problems of estimating the characteristics of the environment and accounting for them in theory. These matters continue to motivate shallow water acoustics research, and provide the challenge for future work in this most difficult branch of underwater sound.

FIG. 1 CHART SHOWING THE SHALLOW WATER AREAS OF THE WORLD

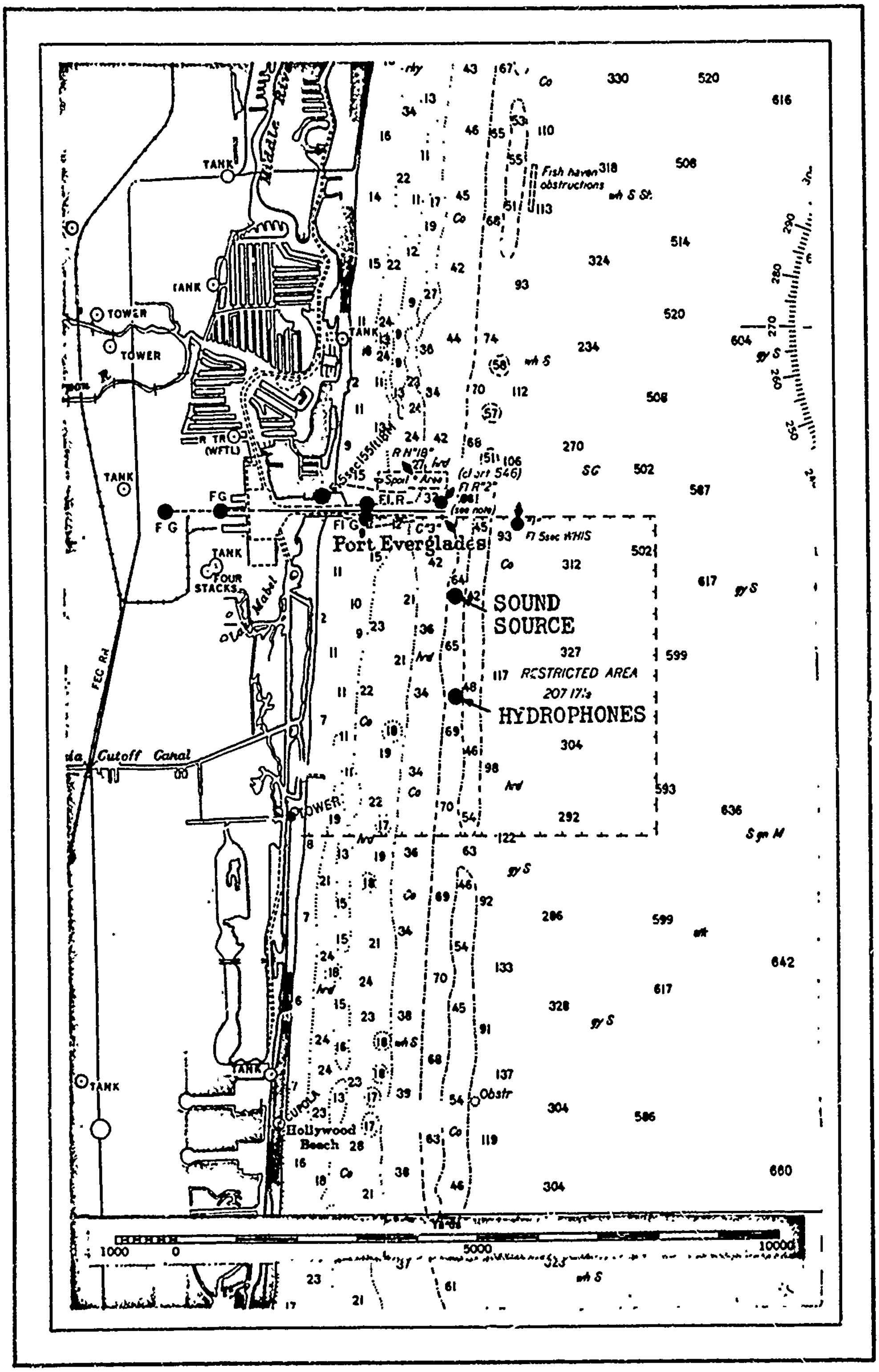


FIG. 2 CHART OF AREA OFF FT. LAUDERDALE, FLA., WHERE A SOUND SOURCE AND A NUMBER OF CLOSE-BY HYDROPHONES WERE PLACED ON THE BOTTOM

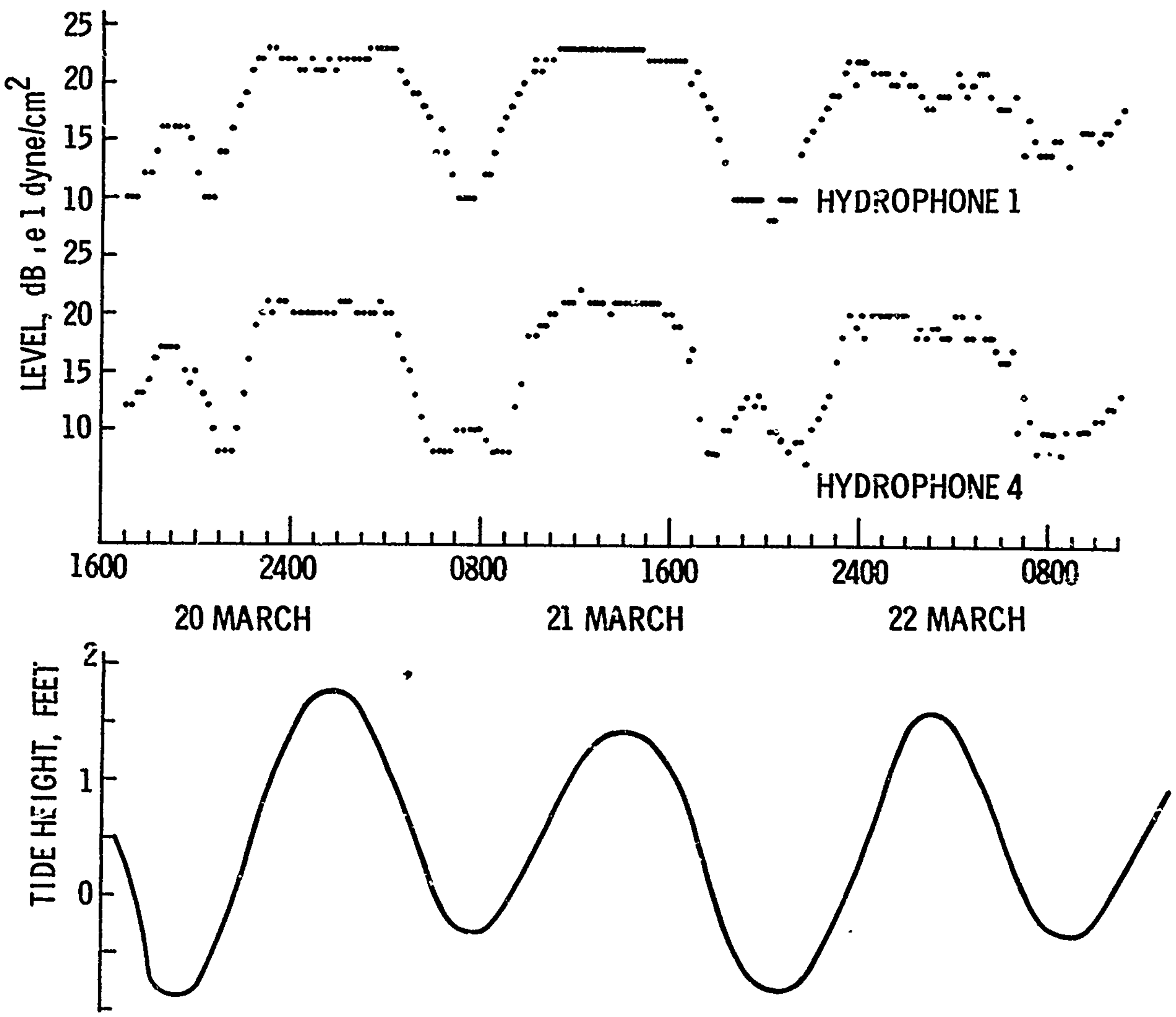


FIG. 3 OBSERVED ACOUSTIC FLUCTUATIONS AT TWO HYDROPHONES 100 FT APART, WITH TIDAL VARIATION FROM TIDE TABLES

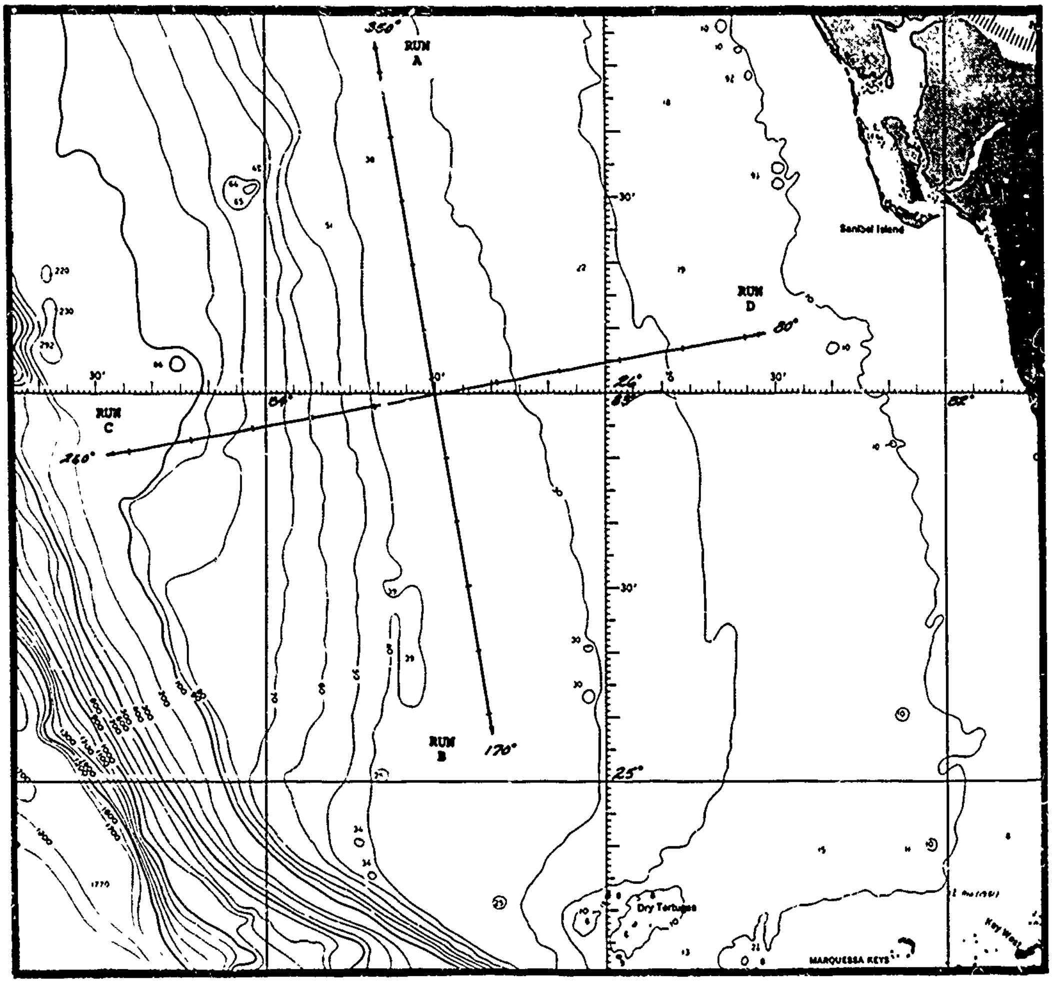


FIG. 4 SITE OFF THE WEST COAST OF FLORIDA WHERE TRANSMISSION DATA WAS COLLECTED

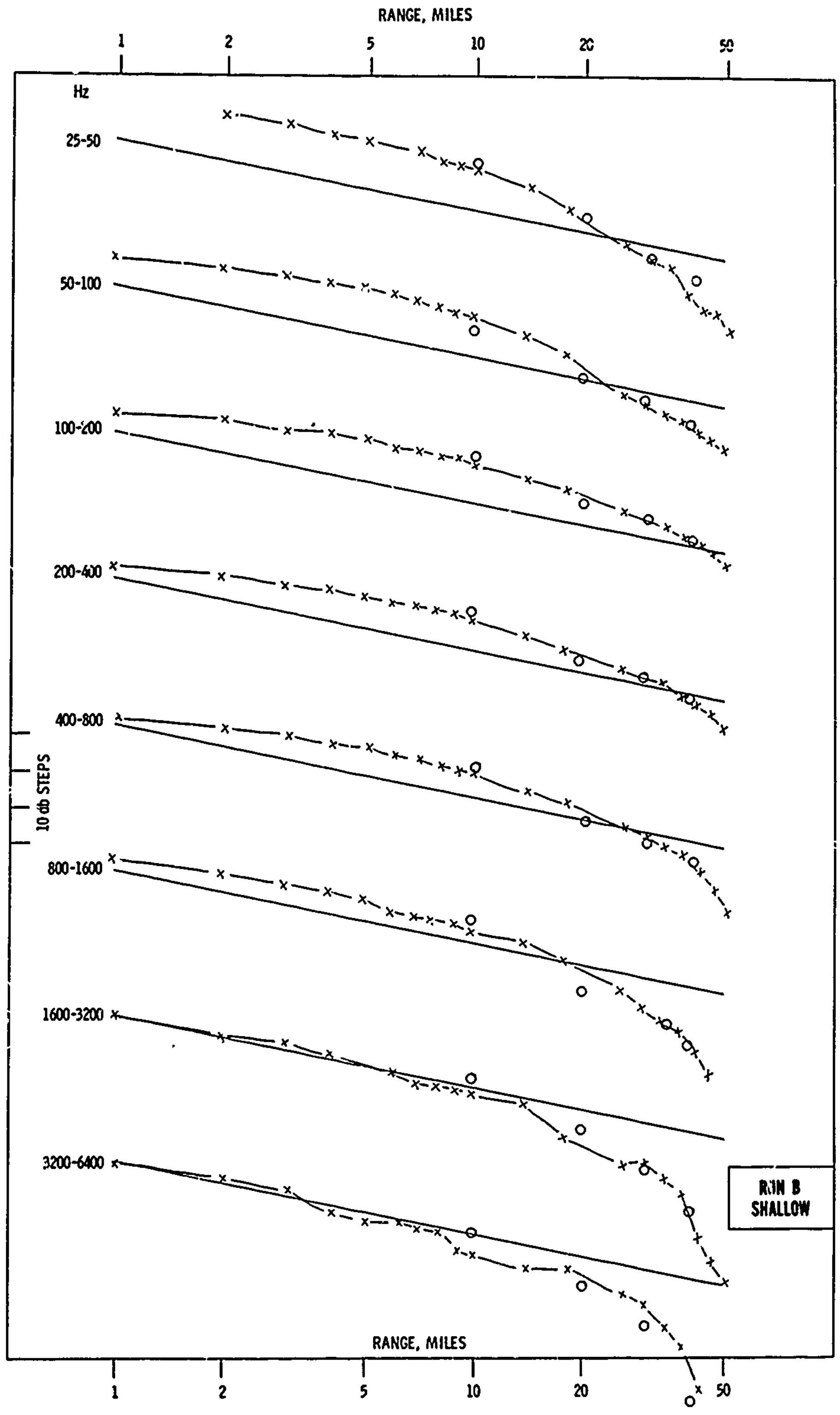


FIG. 5 TRANSMISSION LOSS IN VARIOUS OCTAVE BANDS, RUN B (FIG. 4)

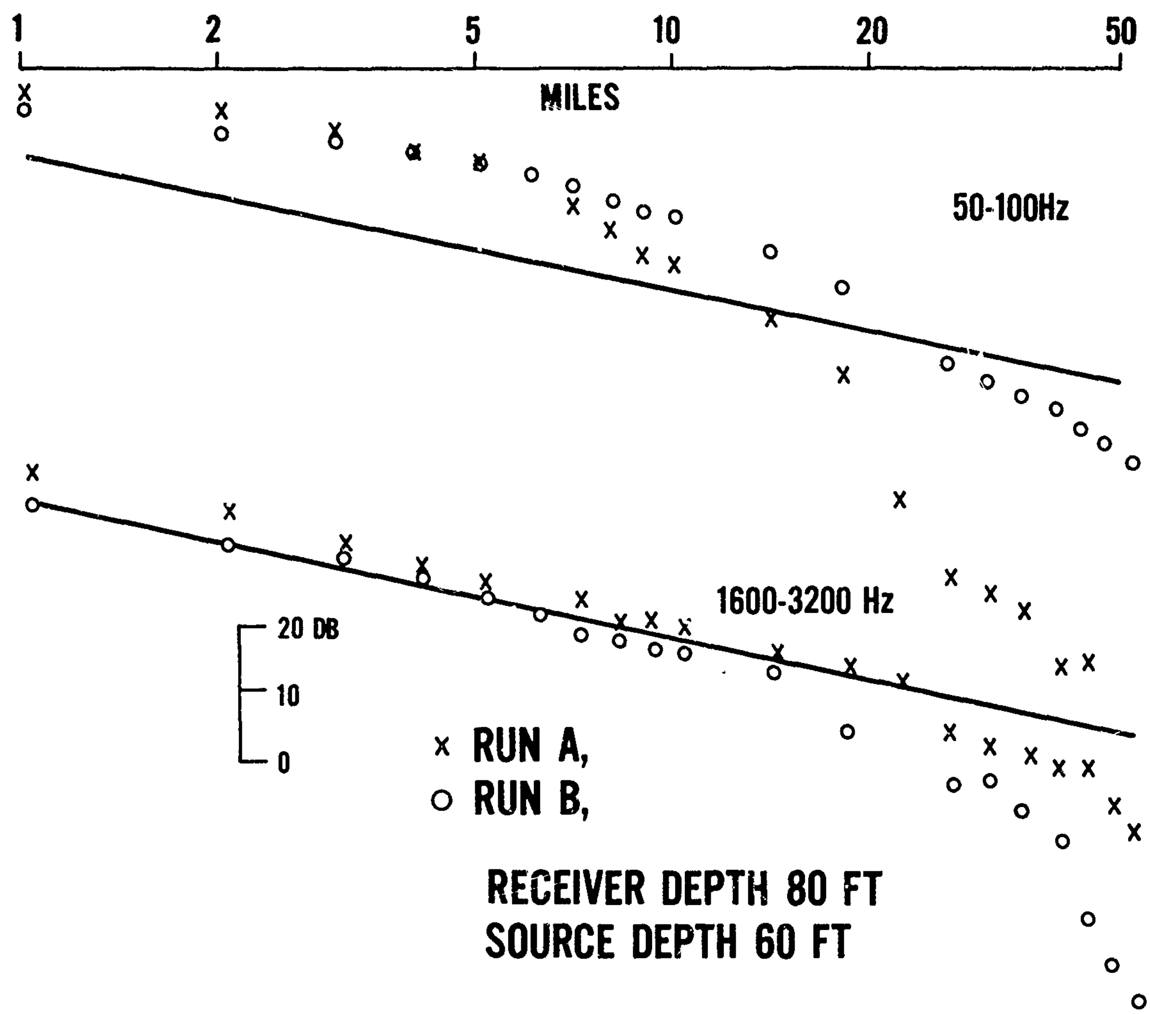


FIG. 6 COMPARISON OF RUN A AND RUN B

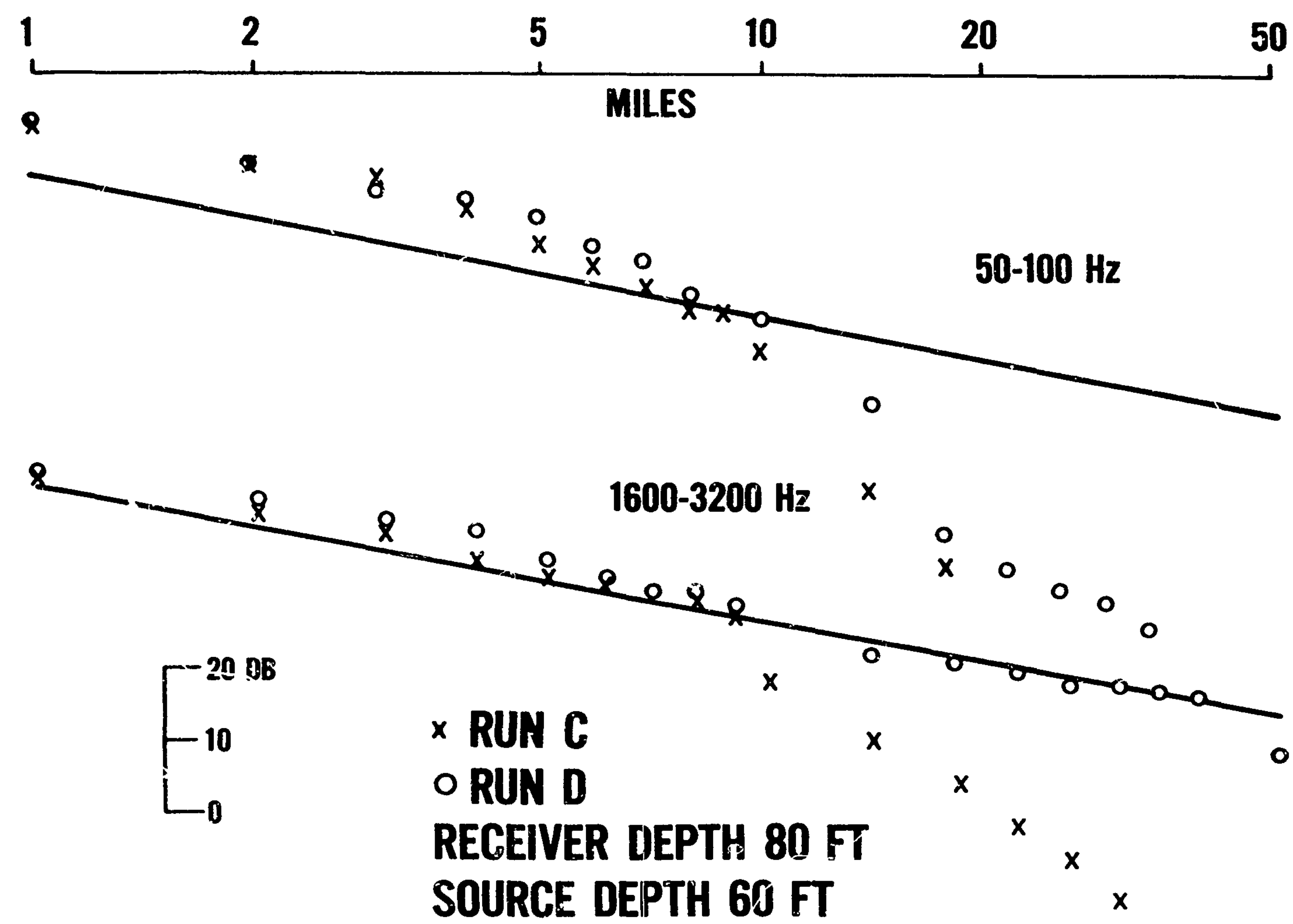


FIG. 7 COMPARISON OF RUN C AND RUN D

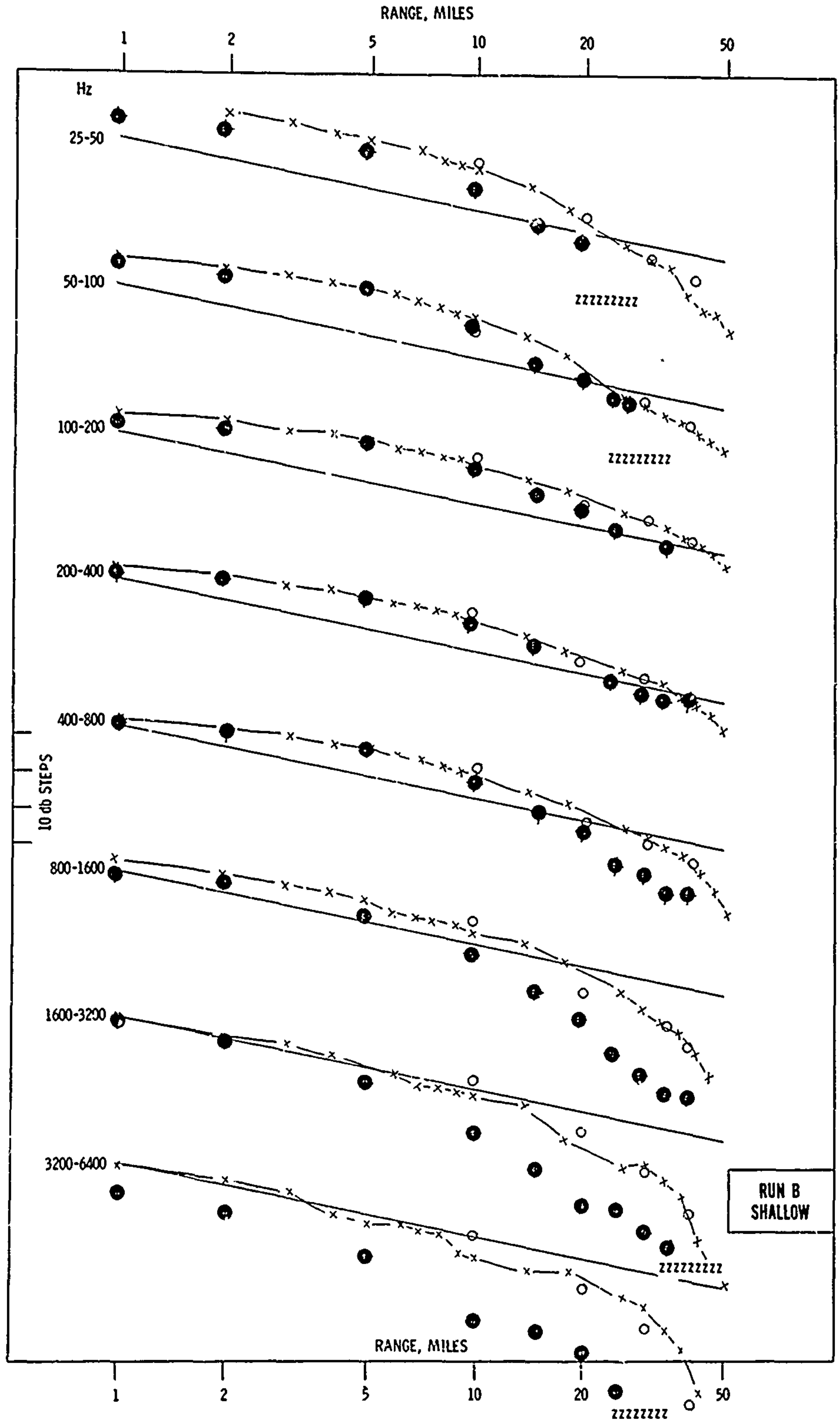


FIG. 8 SEASONAL CHANGES IN TRANSMISSION. LARGE DOTS ARE REPEAT MEASUREMENTS MADE AT ANOTHER TIME OF YEAR

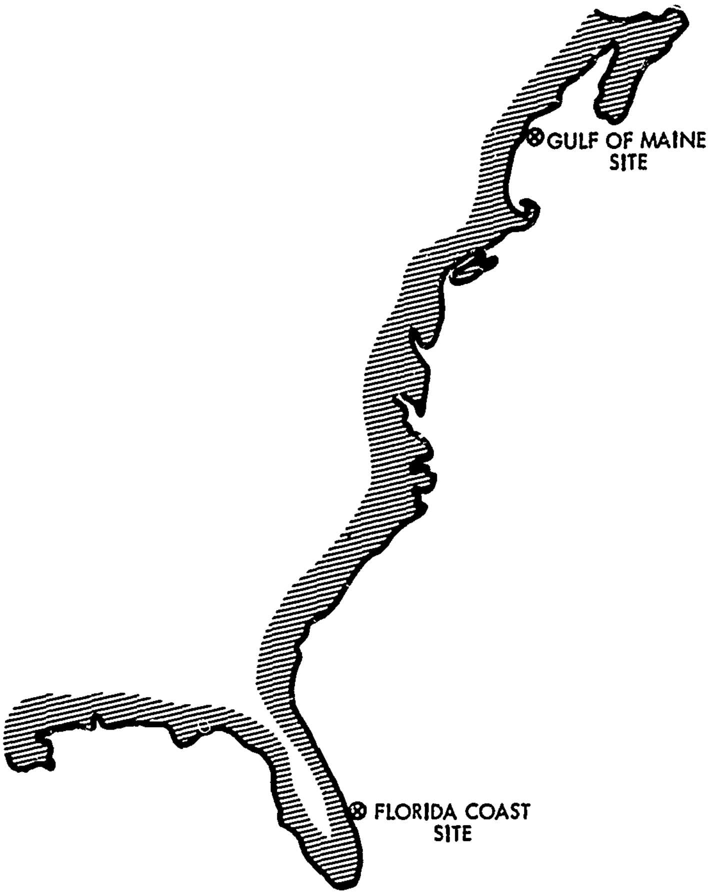


FIG. 9 AMBIENT BACKGROUND MEASUREMENTS SITES

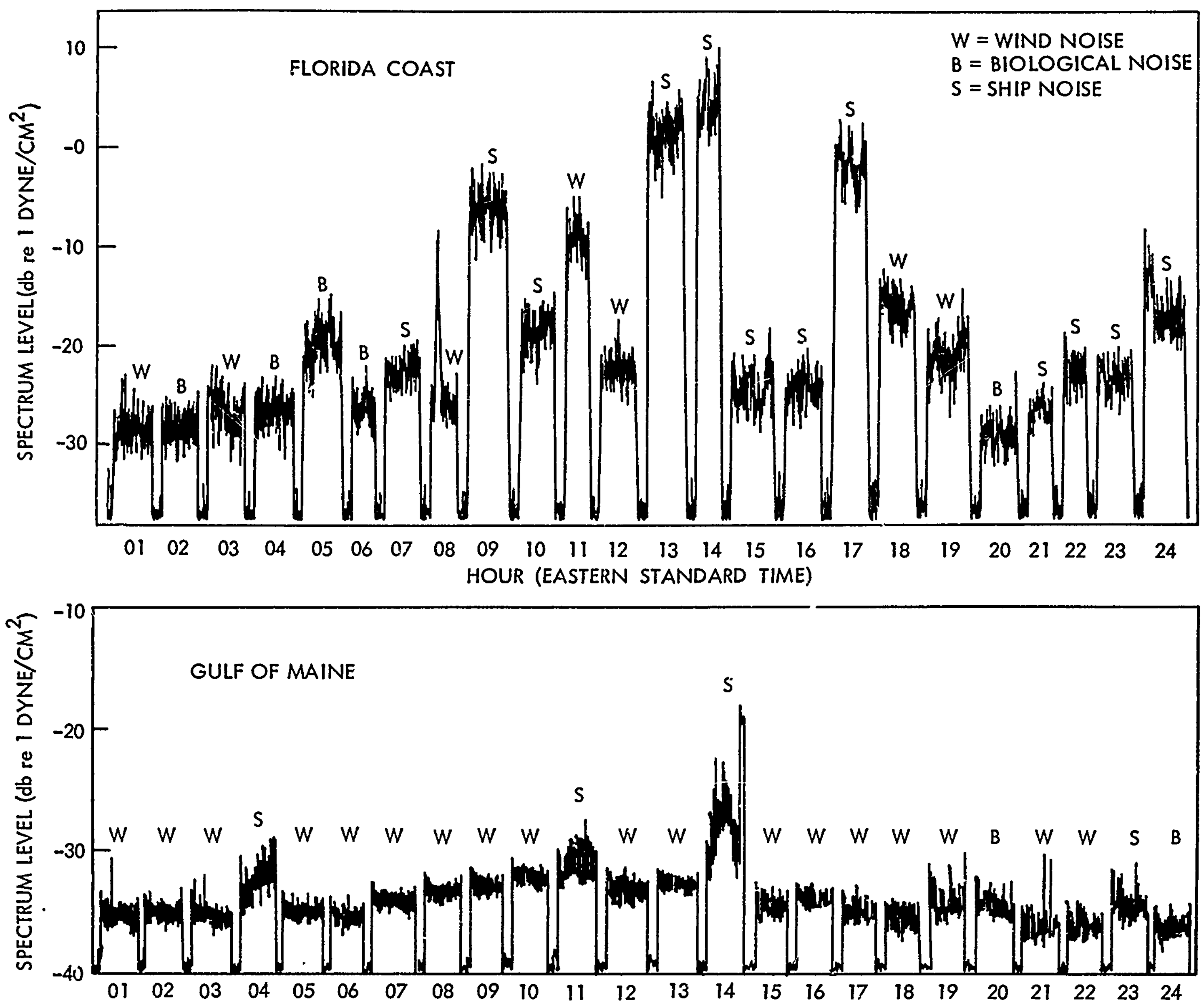


FIG. 10 LEVELS OF SUCCESSIVE ONE-MINUTE HOURLY SAMPLES AT THE TWO SITES

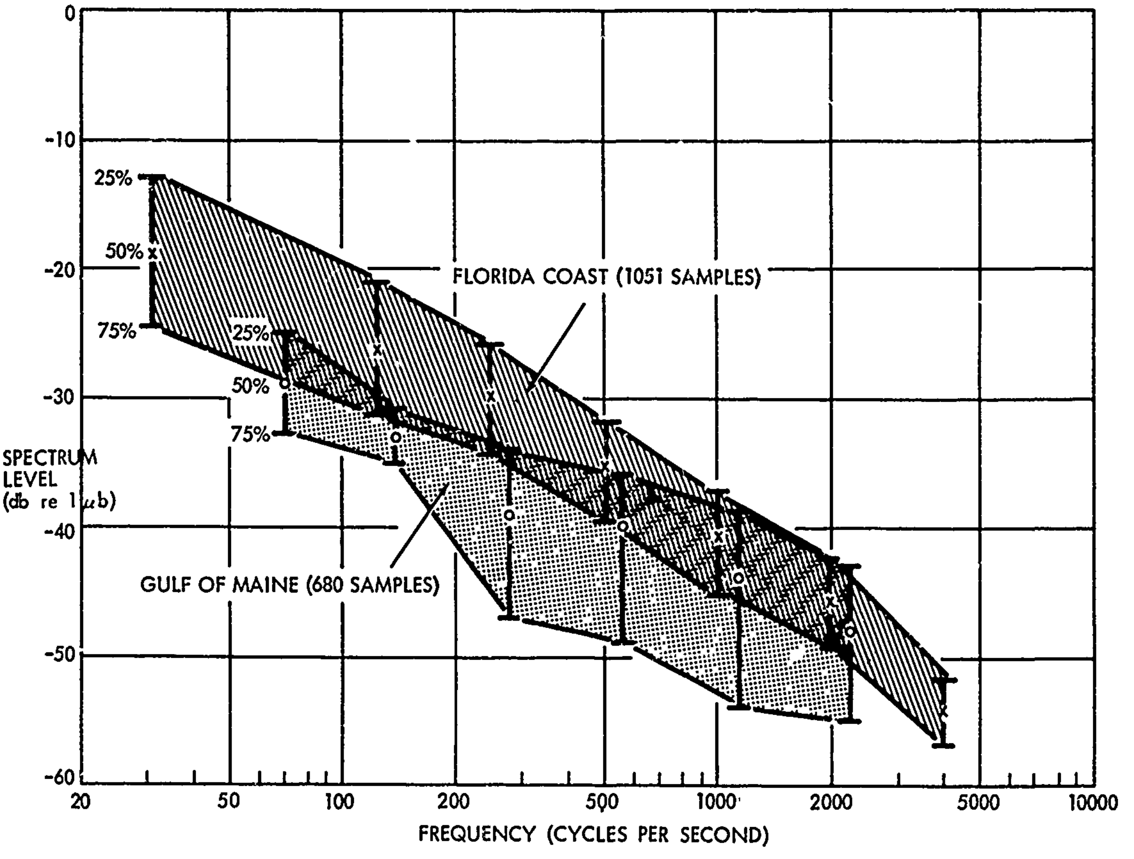


FIG. 11 NOISE LEVEL STATISTICS AT THE TWO SITES

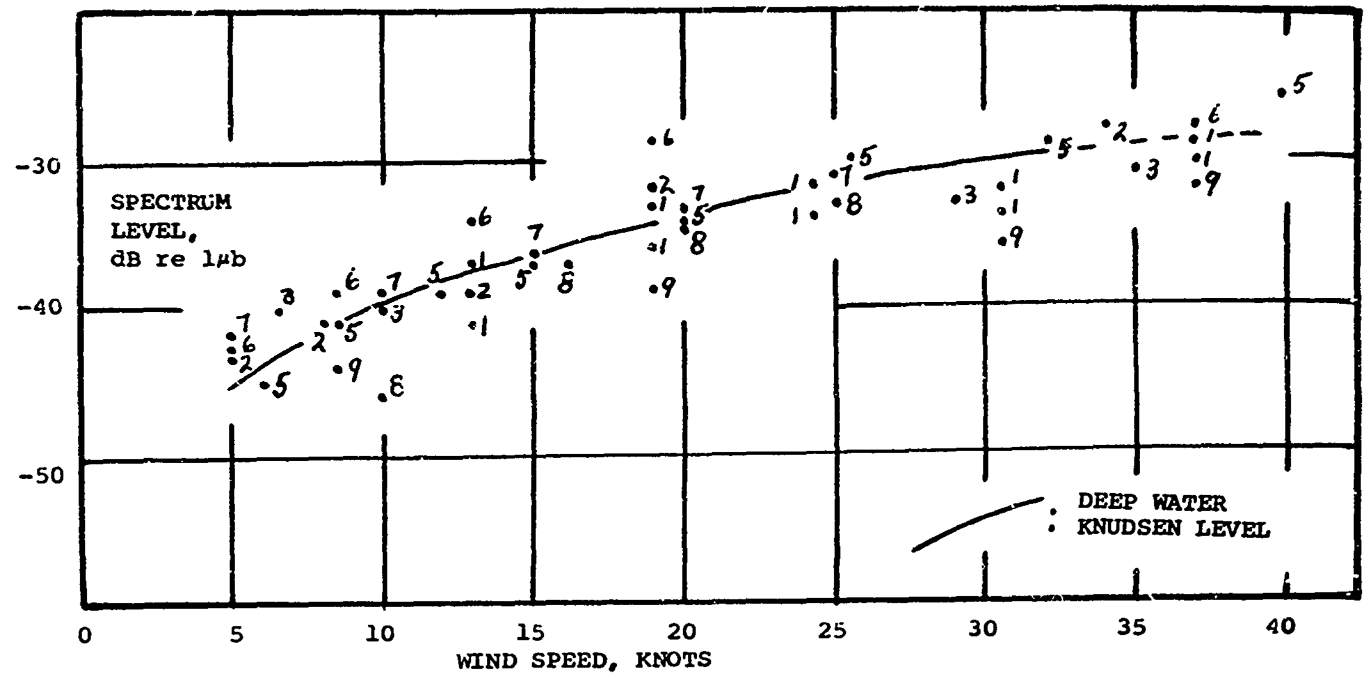
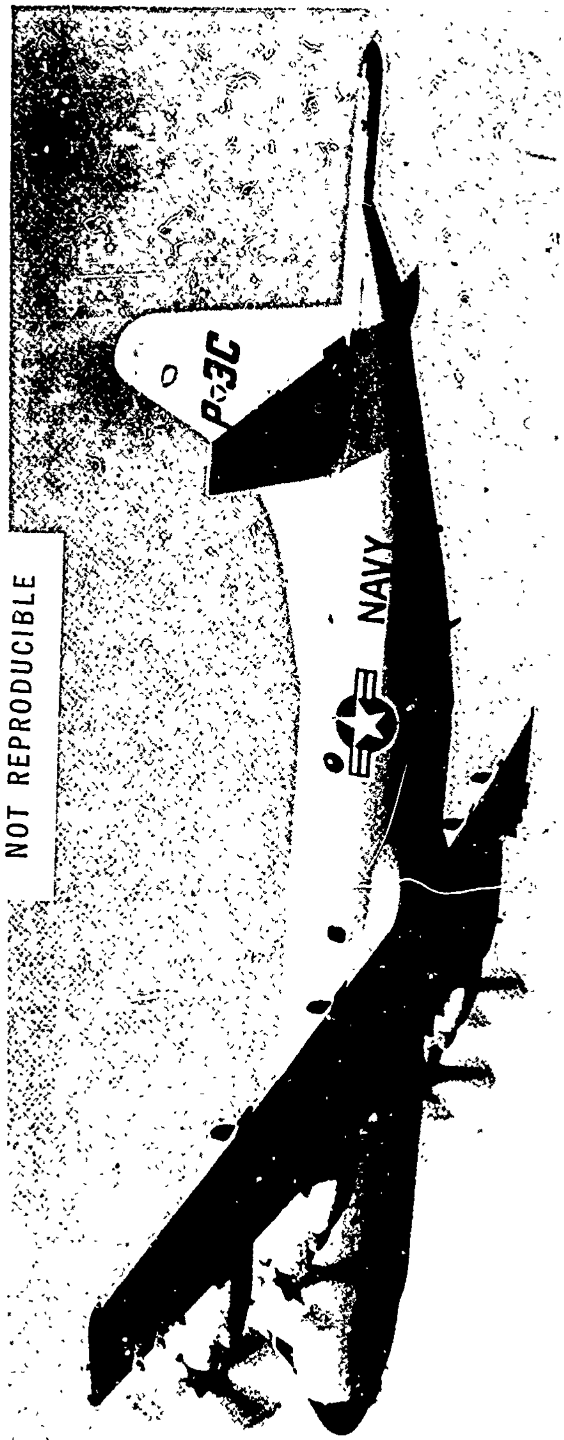
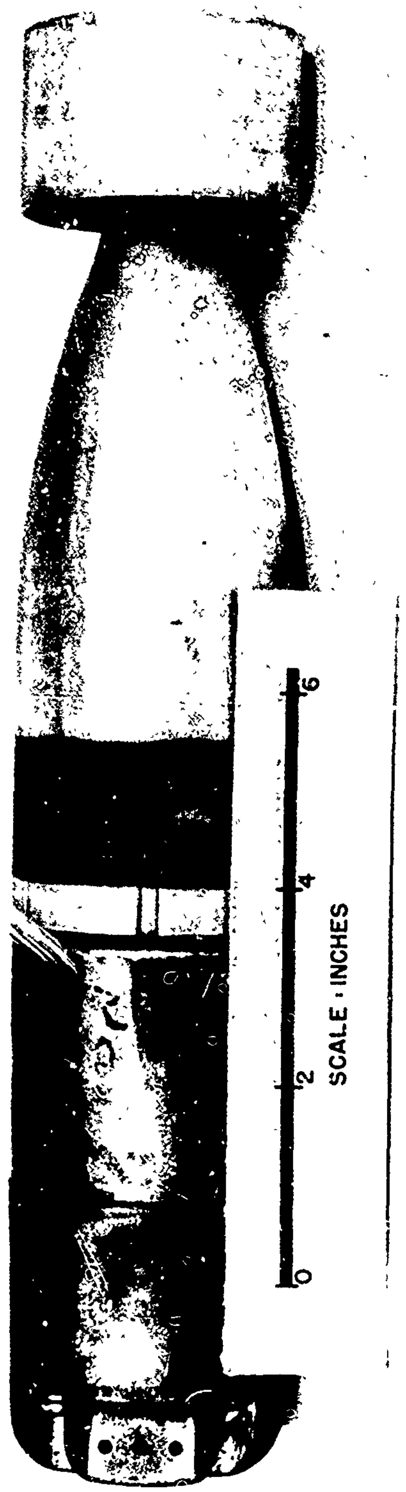


FIG. 12 SPECTRUM LEVEL AT 1000Hz AT VARIOUS LOCATIONS AS REPORTED IN THE LITERATURE. THE NUMBERS ALONGSIDE EACH POINT ARE KEY NUMBERS TO LITERATURE SOURCES



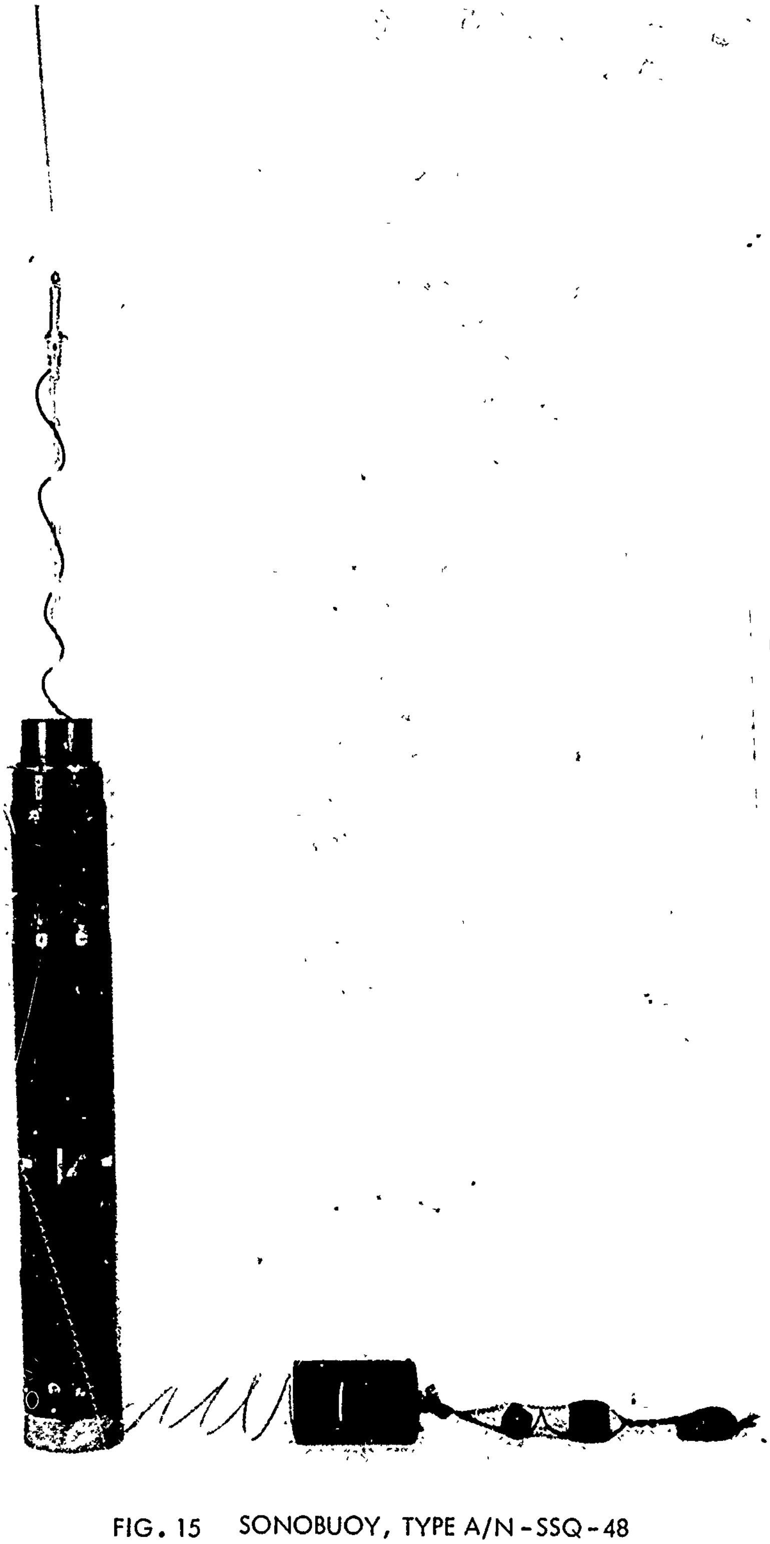
NOT REPRODUCIBLE

FIG. 13 P-3C AIRCRAFT



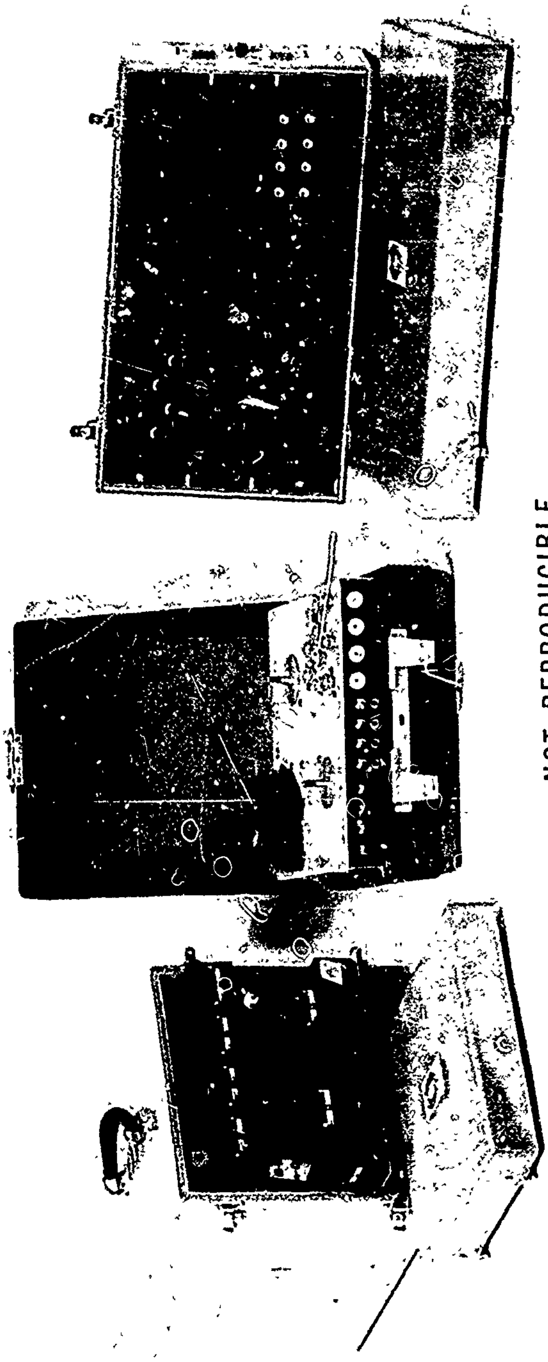
NOT REPRODUCIBLE

FIG. 14 NAVY EXPLOSIVE SOUND SIGNAL



NOT REPRODUCIBLE

FIG. 15 SONOBUOY, TYPE A/N-SSQ-48



NOT REPRODUCIBLE

FIG. 16 RECORDING SYSTEM

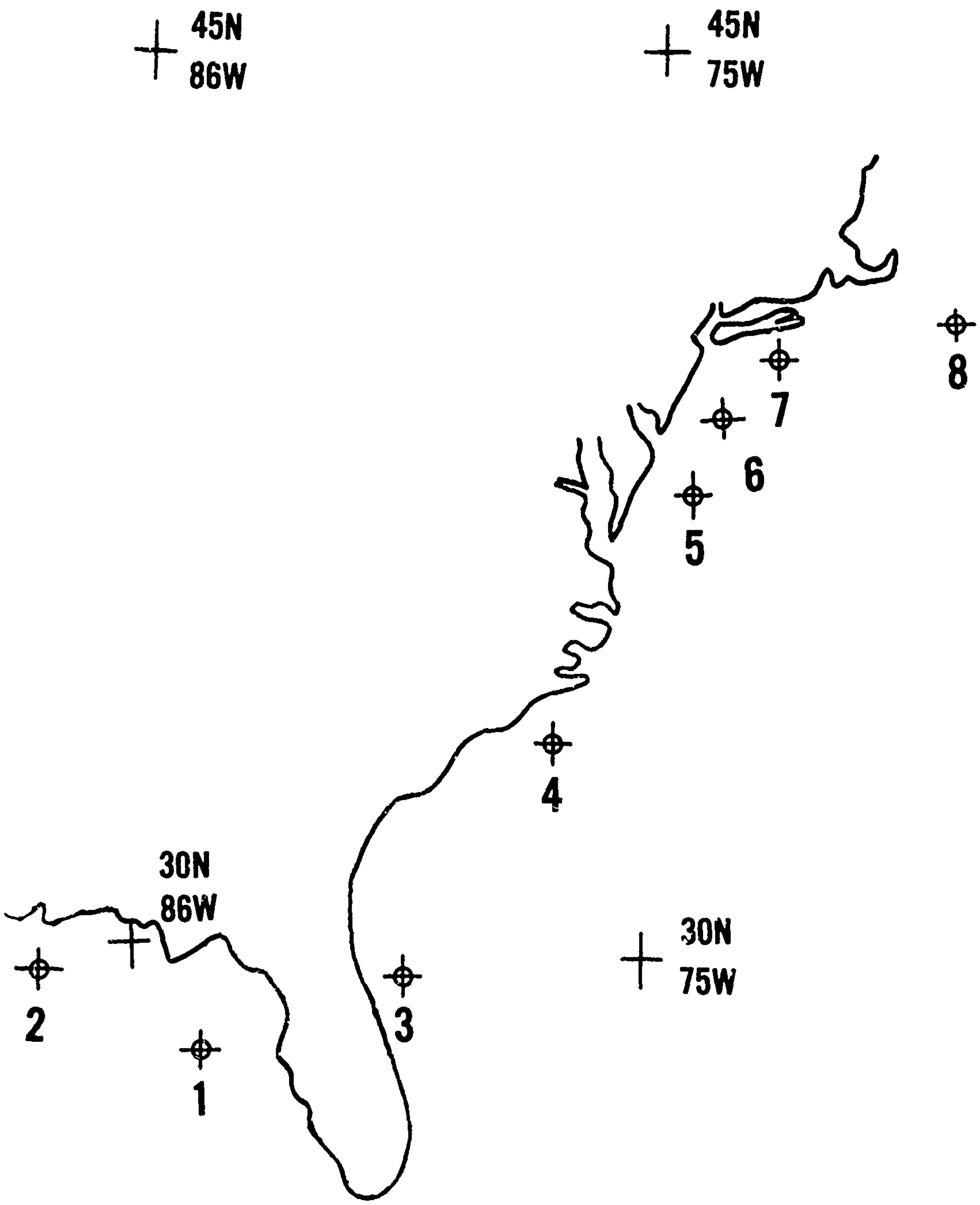


FIG. 17 SITE LOCATION OF SHALLOW WATER MEASUREMENTS

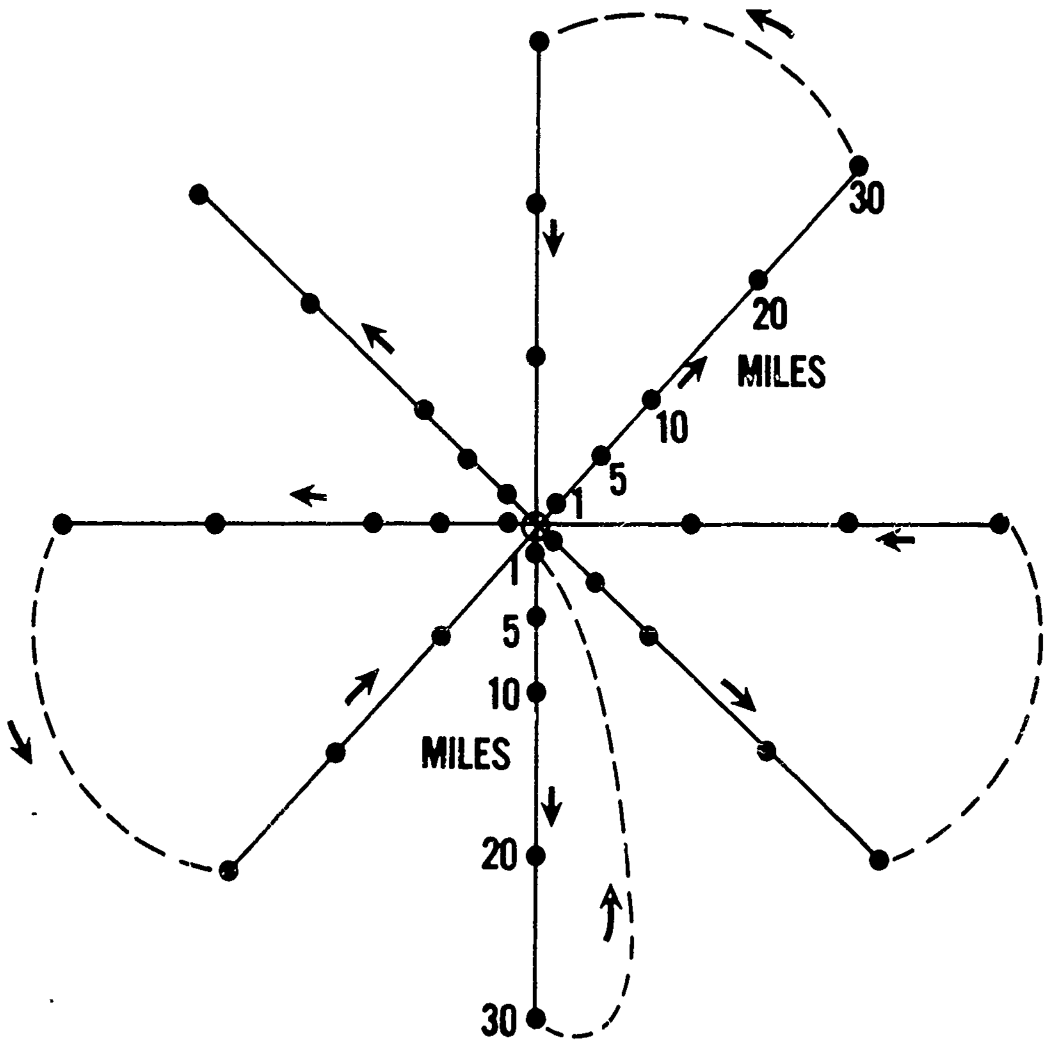


FIG. 18 FLIGHT PATTERN FLOWN AT EACH LOCATION

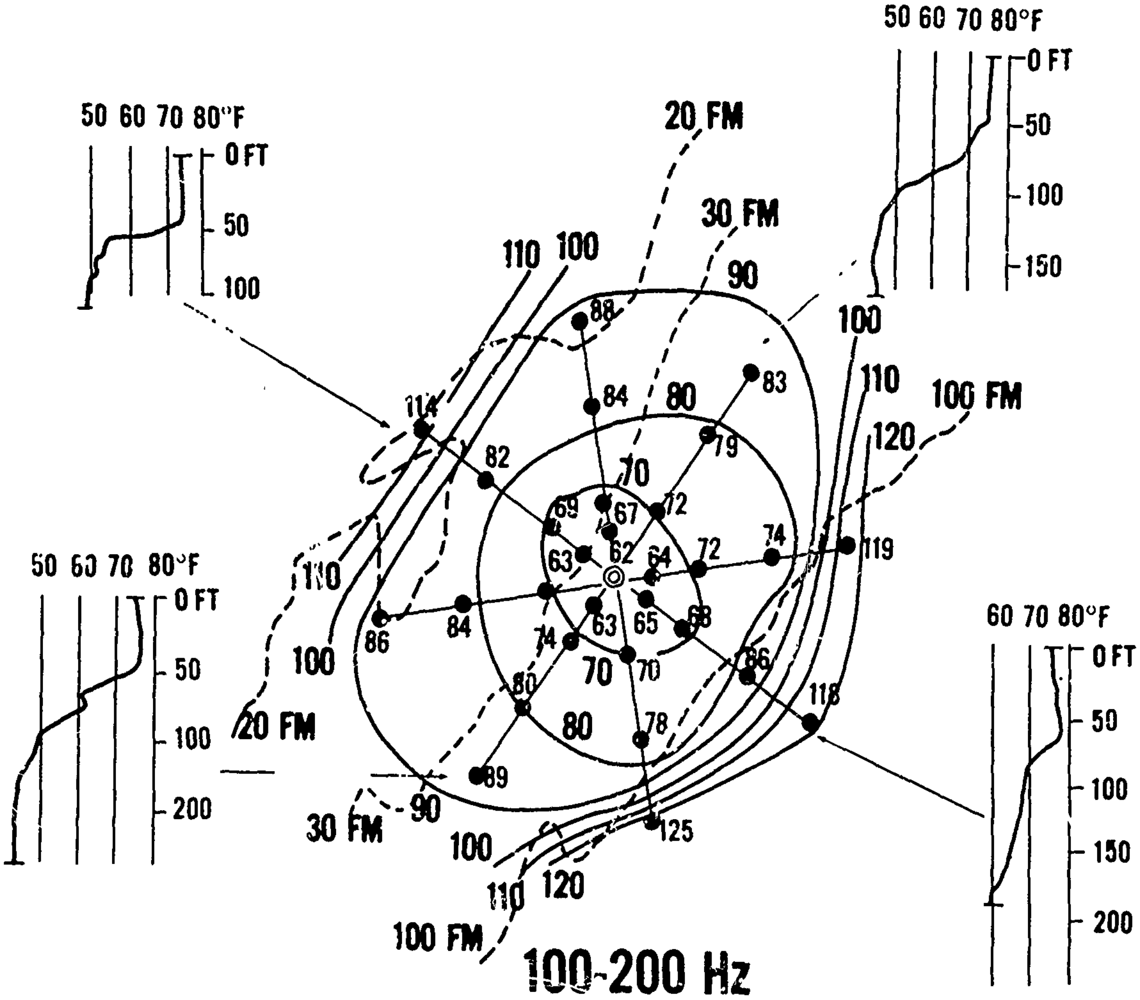


FIG. 19 ACOUSTIC AND ENVIRONMENTAL RESULTS AT ONE LOCATION

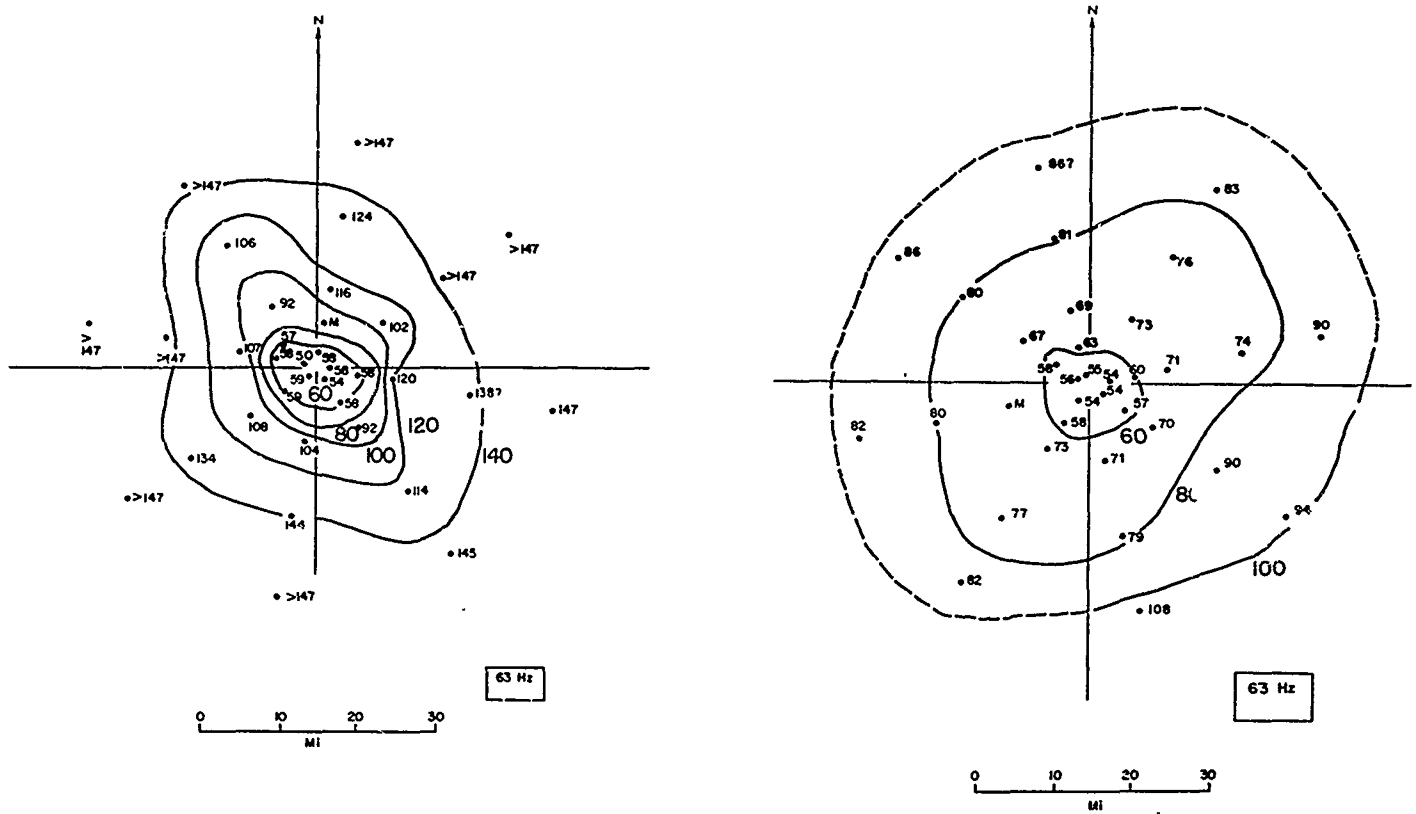


FIG. 20 LOSS CONTOURS IN AN OCTAVE BAND CENTERED AT 63 Hz AT TWO LOCATIONS

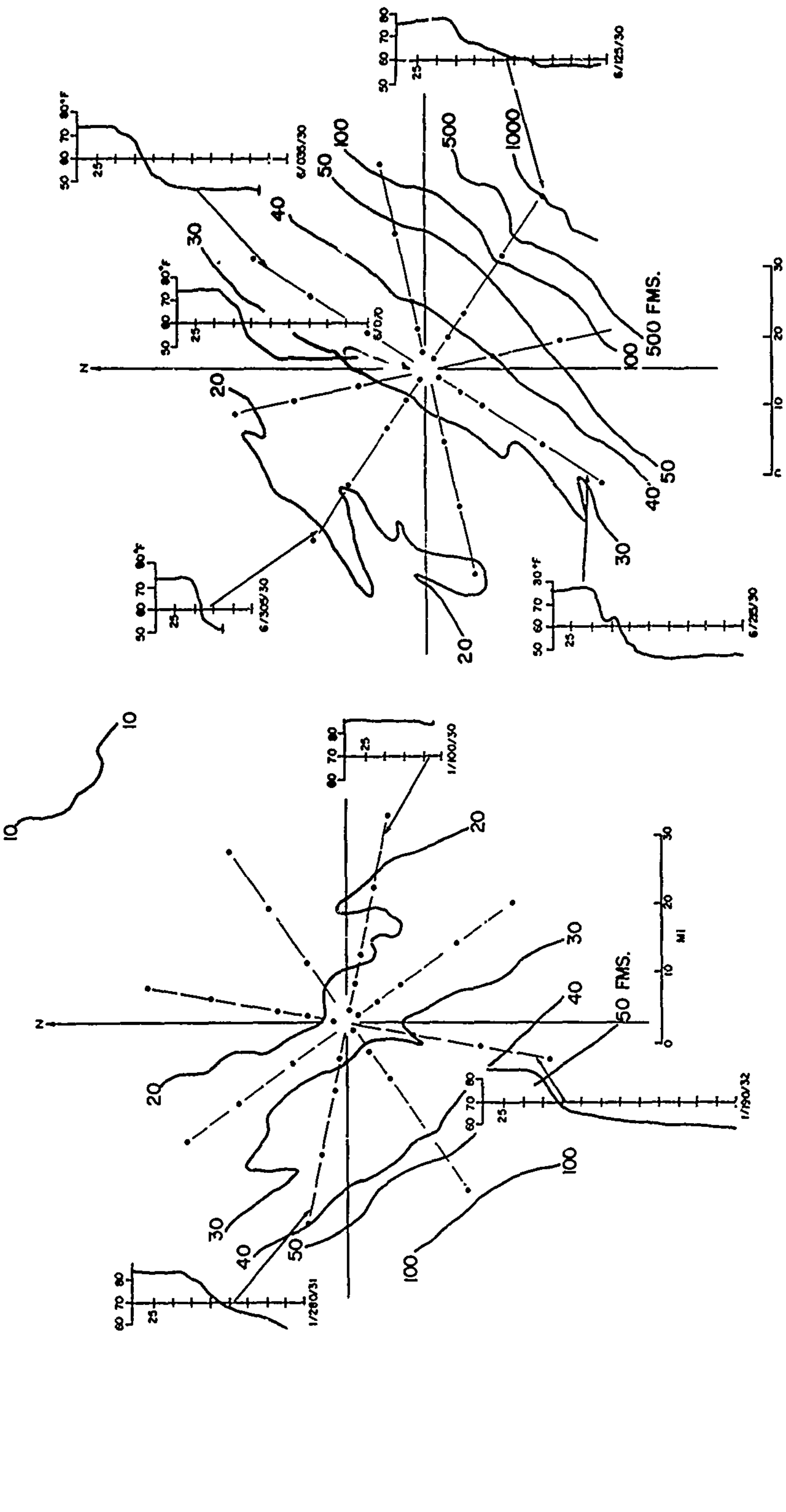


FIG. 21 ENVIRONMENTAL DATA FOR THE TWO LOCATIONS FOR WHICH ACOUSTIC RESULTS ARE GIVEN IN FIG. 20

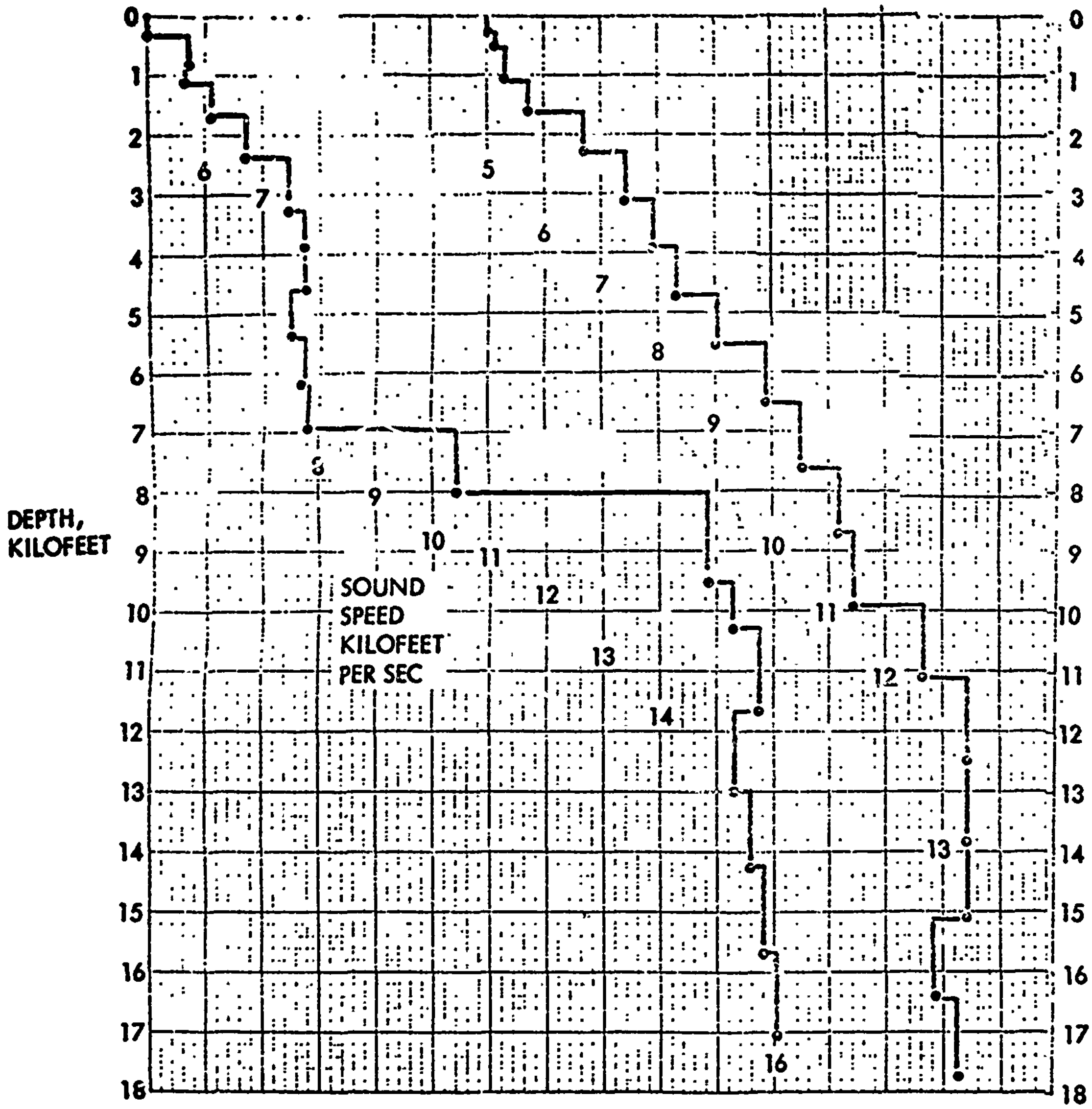


FIG. 22 VELOCITY PROFILES IN THE BOTTOM FOR THE TWO LOCATIONS